Diffuse γ-rays from galactic halos

Martin Pohl

1 Introduction

The γ-ray sky as we know it today is a composite of the emission from point sources and diffuse emission (see Fig.1). The most prominent feature is the galactic plane, in which interactions between cosmic rays and the thermal gas lead to γ-ray emission by π^0-decay and bremsstrahlung. On top of this diffuse emission we see point sources all over the map, part of them being pulsars, another part distant AGN, and also a significant fraction of yet unidentified sources. But we also see that the diffuse emission extends out of the galactic plane up to the poles. There appears to be an isotropic emission component which is presumably extragalactic in origin and may be understood as blend of unresolved AGN, but there is also considerable galactic emission. At higher latitudes interactions between cosmic rays and thermal gas still play a role, but inverse-Compton scattering of ambient photons by cosmic ray electrons becomes increasingly important. This emission tells us about the physical conditions in the halo as seen by the cosmic ray particles, and it may also reveal previously hidden gas, e.g. baryonic dark matter.

2 The rôle of confused point sources

Locally, any analysis of the galactic diffuse emission can be seriously hampered by unresolved galactic point sources which may have a sky distribution similar to that of gas. As is shown in Table 1, in the galactic plane the source density is significantly higher than at high latitudes, not only in total number but especially for the unidentified sources. If the sky distribution of sources were isotropic we would expect a smaller source density in the plane, since the strong background there reduces the statistical prominence of any source even for the on average higher exposure. A modelling of the sky distribution of sources under the assumption that all unidentified sources are galactic has revealed that unresolved galactic sources would account for 30-40% of the total galactic γ-ray luminosity above 100 MeV and that the sky distribution of the unresolved

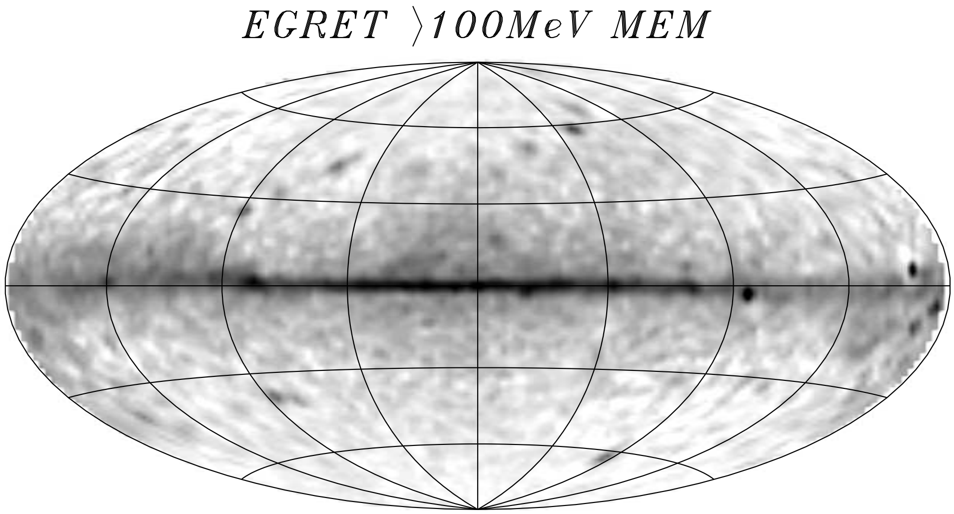

Figure 1: The EGRET sky above 100 MeV γ-ray energy. The image is deconvolved by a Maximum-Entropy algorithm (for the method see Strong 1995). The grey scale is logarithmic with darkness indicating high intensity.

sources could resemble that of the gas since we see mainly the more distant sources (Kanbach et al. 1996). Although in reality the numbers may not be that bad, perhaps around 20%, for halo studies the point source contribution has to be taken into account.

|b|	[sr]	Identified	Unidentified	Identified/Total	Total/steradian
0-10	2.2	5	32	0.14 ± 0.06	16 ± 3.0
10-30	4.1	18	26	0.41 ± 0.11	11 ± 1.6
30-90	6.3	32	14	0.70 ± 0.16	7.3 ± 1.1

Table 1: Source statistic on the basis of the second EGRET catalog (Thompson et al. 1995). In the galactic plane the source density is higher than at high latitudes and also the fraction of identified sources is unusually small.

If there were no point sources the γ-ray intensity in the galactic plane should follow locally the gas distribution. In fact the EGRET team uses a scaling model on the basis of the gas distribution as null hypothesis in the search for point sources (Hunter et al. 1996). We can test the reliability of such

models on small scales by comparing it to deconvolved data for the galactic center region where the statistic is best, i.e. small scale structures have the highest statistical significance. We will concentrate on data at higher energies where EGRET's point spread function is smaller and less photons are required to reproduce the intensity structure. The result is shown in Fig.2 and Fig.3, where despite the larger pixel size in the model (Fig.3) it is obvious that there is a wealth of structure not directly related to the gas. Part of this additional structure is listed as unidentified sources in the second EGRET catalog.

It should be noted that comparing deconvolved data to the original data is more sensitive to small scale discrepancies than the usual comparison of a convolved model to original data, especially if the global sky distribution of point sources is similar to the distribution of gas. Therefore, our finding does not contradict the statement of Hunter et al. (1996) that the gas coupling model, convolved and averaged over strips a few degrees wide, is a good representation of the observed sky distribution at γ-ray energies above 100 MeV.

3 Diffuse emission in the EGRET range

3.1 The γ-ray emissivity

In galactic halos inverse-Compton scattering (IC) of ambient photons by cosmic ray electrons is an important production process for γ-rays . Due to the large scale heights of far-infrared photons and the cosmic microwave background, the latitude distribution of this emission is much broader than in case of the bremsstrahlung and π^0-decay. Thus the IC component can tell us about the lifetime of cosmic ray electrons in the Galactic halo. Unfortunately the IC emission is generally weak and has a spectral shape similar to that of the extragalactic γ-ray background. However, the latter should be isotropic, and one may use the contrast between inner and outer Galaxy to detect the IC component.

One may also compare the spatial distribution of γ-rays not related to gas to the brightness temperature distribution in radio surveys. Depending on frequency the bulk of radio emission at high latitudes will be due to synchrotron radiation of cosmic ray electrons, and one should expect correlations between the synchrotron flux density and the IC intensity, although the typical electron energy for synchrotron emission at 408 MHz is roughly an order of magnitude less than the energy required for up-scattering infrared photons. Such work has

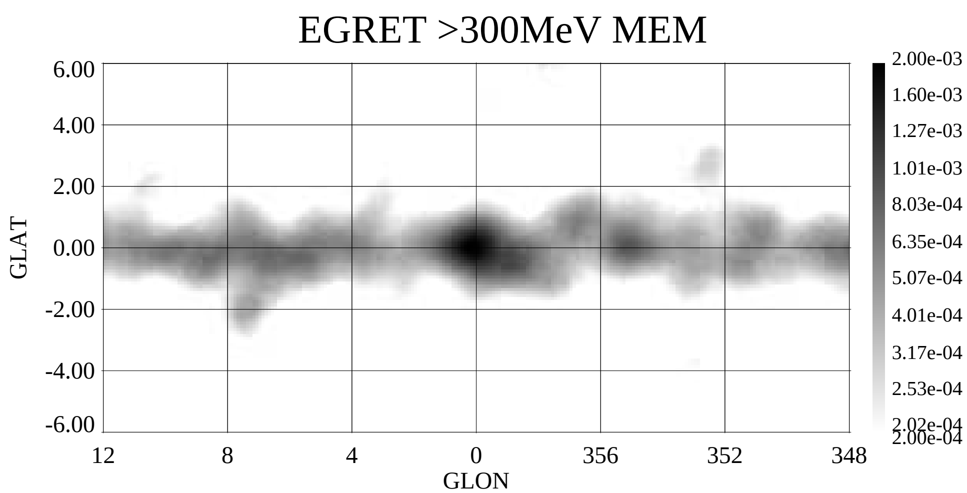

Figure 2: The galactic center region above 300 MeV γ-ray energy. The image is deconvolved by a Maximum-Entropy algorithm. The intensity scale is in units $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}$.

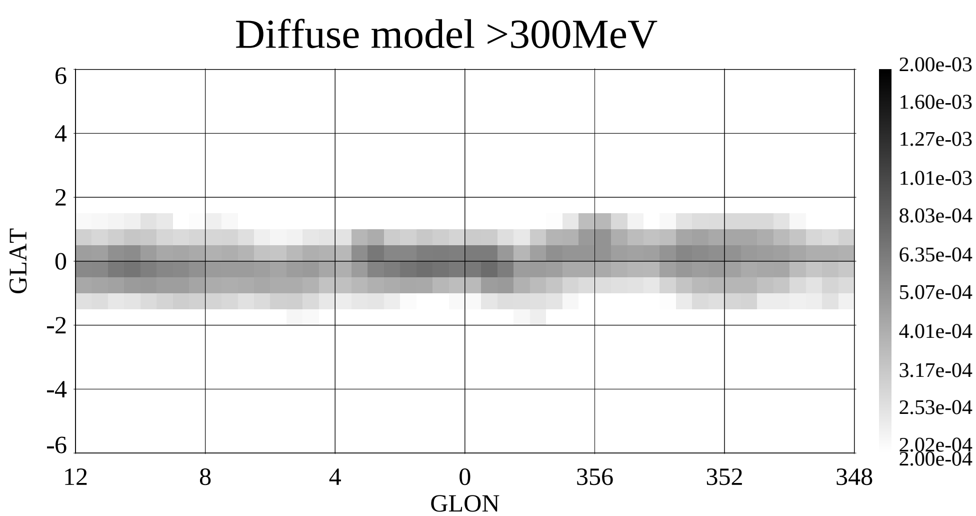

Figure 3: The model prediction based on gas distribution for the galactic center region. The scale is the same as for the deconvolved EGRET data in Fig.2. The disagreement between Fig.2 and Fig.3 is obvious, implying that point sources contribute significantly.

been done by Chen et al. (1996), who conclude that the average intensity of IC emission at high latitudes is $(5 \pm 0.8) \cdot 10^{-6}$ cm^{-2} sec^{-1} sr^{-1} for $E > 100$ MeV (around one third of the diffuse extragalactic background) and that the photon spectral index is -1.85 ± 0.17.

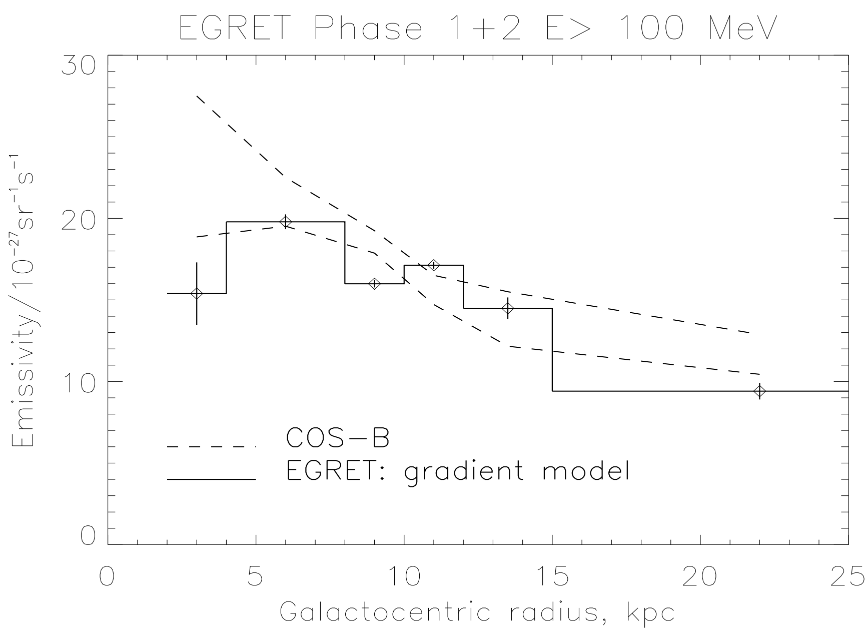

Figure 4: The γ-ray emissivity per H-atom averaged over galactocentric rings. There is weak decrease of emissivity with galactocentric radius, the so-called gradient, basically confirming the earlier COS-B result. (Strong and Mattox 1996)

To investigate the γ-ray emission originating from π^0-decay and bremsstrahlung we need some prior knowledge on the distribution of gas in the Galaxy. This includes not only HI but also H_2, which is indirectly traced by CO emission lines, and HII, which is traced by Hα and pulsar dispersion measurements. Even in case of the directly observable atomic hydrogen we obtain only line-of-sight integrals, albeit with some kinematical information. Any deconvolution of the velocity shifts into distance is hampered by the line broadening of individual gas clouds and by the proper motion of clouds with respect to the main rotation flow. The distance uncertainty will in general be around 1 kpc.

It may be appropriate to use only a few resolution elements and investigate

the γ-ray emissivity per H-atom in galactocentric rings, i.e. to assume azimuthal symmetry for the emissivity. This kind of approach has already been successfully applied to the earlier COS-B data. Strong and Mattox (1996) have repeated the analysis on EGRET data at γ-ray energies above 100 MeV. These authors report that there is a gradient, that is a decline of the γ-ray emissivity per H-atom with galactocentric radius, confirming earlier COS-B results. This radial gradient is weak and does not exceed a factor 2 difference between inner and outer Galaxy (see also Fig.4). It should be noted that this gradient does not necessarily hold locally. A comparison of the γ-ray emissivity in the perseus arm at 3 kpc distance in the outer galaxy to the Cepheus and Polaris flare at 250 pc gave a difference of a factor 1.7$\pm$0.2, by far exceeding the overall gradient (Digel et al. 1996).

3.2 Spectral information

The γ-ray production processes may not only be separable by their different sky distribution, but also by their spectral shapes. While the π^0-decay should result in a broad line centered on 68 MeV, the bremsstrahlung spectrum should follow the rather steep electron spectrum, thereby partly hiding the signature of the π^0-decay line. The emission due to IC scattering is expected to have a hard spectrum, similar to that of the diffuse extragalactic background. Strong and Mattox (1996) have performed a spectral analysis of EGRET data in the ten standard energy bands to investigate the spectrum of the isotropic extragalactic emission, the emission correlated to the gas distribution (π^0-decay and bremsstrahlung), and the emission due to IC scattering, for which the expected sky distribution was modelled. The result is shown in Fig.5 together with the overall spectrum of diffuse emission in EGRET data compared to the results of COMPTEL and the earlier mission COS-B. All sources in the second EGRET catalog have been taken into account in this analysis.

The spectrum of the isotropic extragalactic component is around E^{-2}, harmonizing with the average AGN spectrum. The IC emission has a slightly harder spectrum similar to the results of Chen et al. (1996) at higher latitudes. However, the spectrum of emission related to the gas is difficult to understand. It deviates significantly from the expected superposition of π^0-decay and bremsstrahlung. At energies above 1 GeV there is a clear excess of emission related to gas which may be somewhat relaxed by variation of the input proton spectrum to the pion production process. Part of this excess may also be explained by unresolved sources, however the small intensity at low

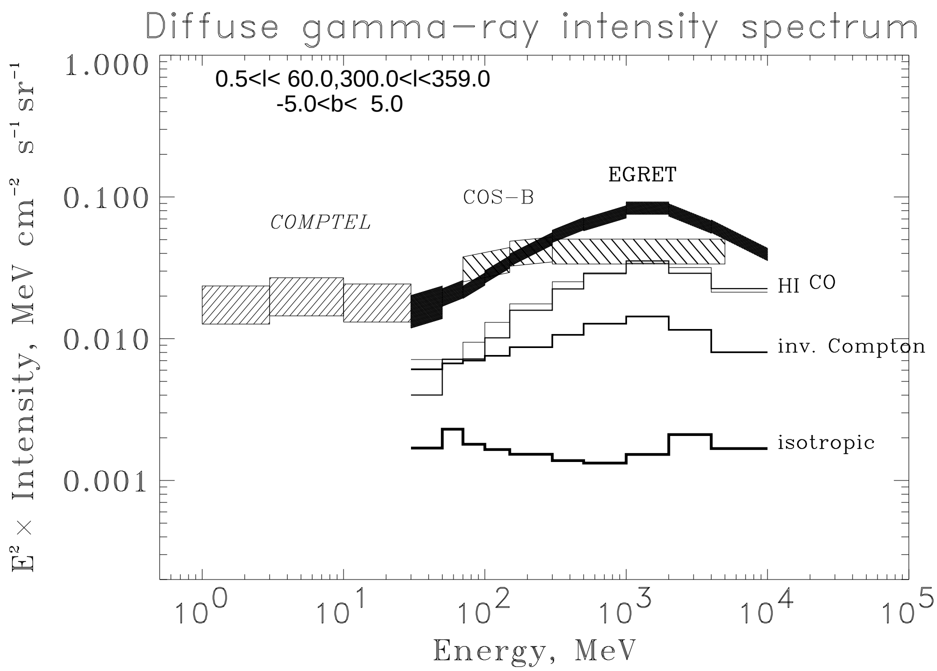

Figure 5: The γ-ray intensity in EF(E) representation. Shown is both the total spectrum (black boxes) and the spectra of the individual components (as histograms) for the inner Galaxy. For comparison the COMPTEL results at lower energies and the old COS-B data are included. The uncertainties in the spectrum of the individual components are around 10% except for the low-energy points. (Strong and Mattox 1996)

energies requires sources with very hard spectrum and possibly a cut-off at a few GeV. Only old pulsars like Geminga have a corresponding spectrum and may also have a sky distribution resembling that of gas.

The spectral hardness of the emission related to gas at low energies is also not easy to understand. The standard analysis tools of EGRET for diffuse emission implicitly assume a power-law spectrum of photon index 2.1. If the true intensity is softer than this the standard analysis will underestimate the emission at low energies, while for hard spectra the emission will be overestimated. The reason for this is that a significant part of the low energy counts are due to misinterpreted photons of higher true energy. An example of this effect is shown in Fig.6. It turns out that even in the absence of any sky emission below

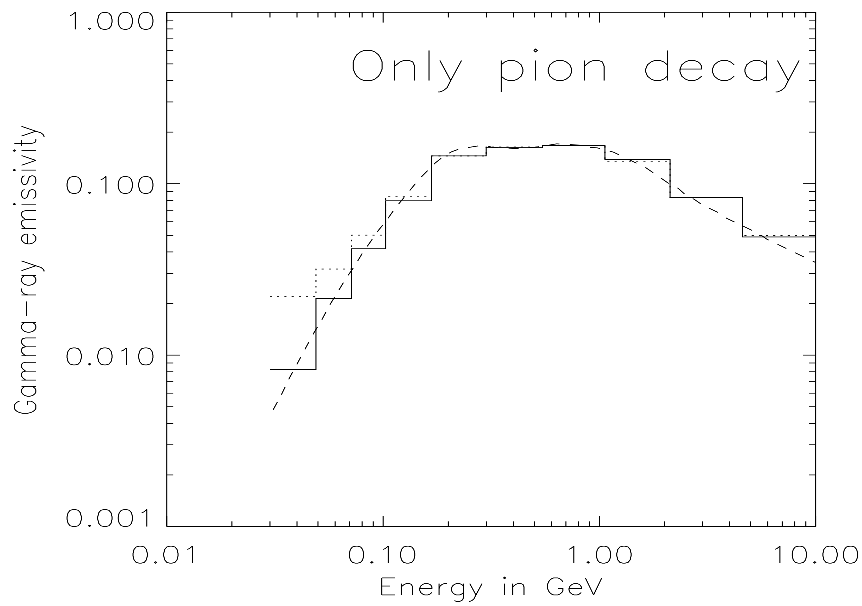

Figure 6: A demonstration of the spill-over effect at low energies. The dashed curve is the true input spectrum in EF(E) representation of arbitrary units, here a π^0-decay spectrum. The solid line histogram is the corresponding average over the standard EGRET energy bands. The dotted histogram shows what the result of the standard EGRET analysis would be. At low energies the spectrum is overestimated by a factor of three.

100 MeV the spill-over provides roughly an E^{-1} differential photon spectrum at these energies. The spectrum of the emission related to gas in Fig.5 is not far from this, indicating that the true sky intensity at low energies is even less. This would imply that the density of 100 MeV electrons is relatively small compared to the density of 10 GeV electrons which are responsible for the IC emission, considering also the radio synchrotron data which tell about the electron spectrum in the GeV range.

4 Diffuse emission at hard X-rays and soft γ-rays

At lower energies we have data from three instruments for the inner Galaxy: COMPTEL in the MeV range (Strong et al. 1994), OSSE in the 100 keV range (Purcell et al. 1996), and GINGA around 10 keV (Yamasaki et al. 1996). The

resulting spectrum of diffuse emission from 2 keV to 30 MeV is shown in Fig.7.

The GINGA spectrum may partly be thermal in origin. In fact a thermal model plus absorbed power-law fits well to the data. Also note the prominent Fe Kα line at 6.7 keV. While the point source contribution in the COMPTEL range is probably around 20% as in case of EGRET, the confusion in the OSSE range is less easy to estimate. OSSE is a non-imaging instrument and therefore cannot identify point sources on its own. The galactic center region has been simultaneously observed by SIGMA, a coded-mask instrument designed to search for sources. It turned out that after subtracting the flux due to point sources resolved by SIGMA the residual OSSE diffuse emission was similar to the total OSSE flux at l=25°, which supports the view that the residual is extended diffuse emission (Purcell et al. 1996). We show only the residual flux in Fig.7, for which still the contamination by unresolved sources is hard to estimate, but is unlikely to account for all the emission.

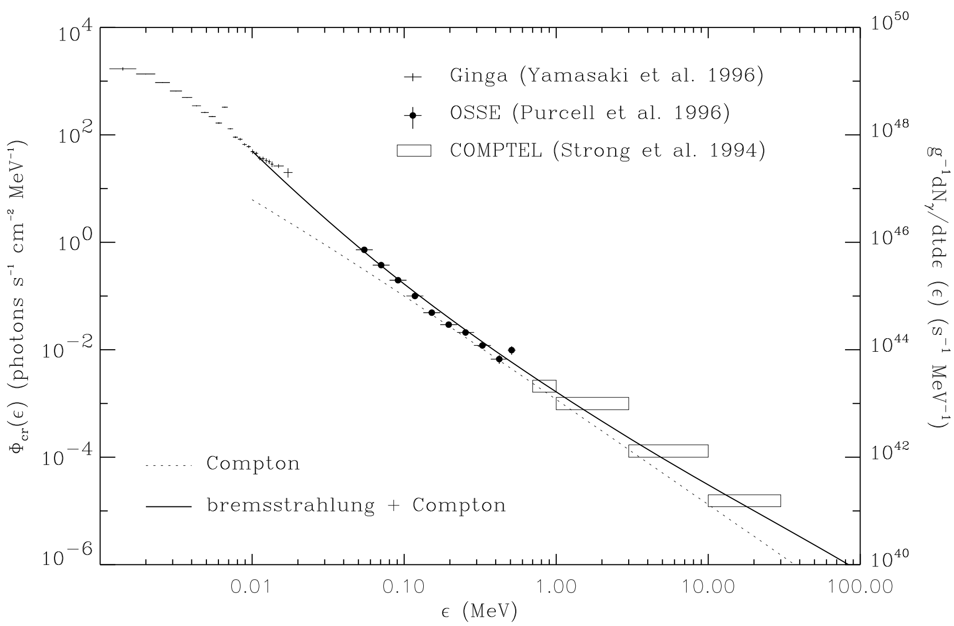

Figure 7: The γ-ray intensity in direction of the inner Galaxy from X-rays to soft γ-rays . The GINGA spectrum may partly be thermal in origin. However, the OSSE data require a very soft electron spectrum at low energies. The solid line is a model curve of bremsstrahlung and IC scattering based on such a soft electron spectrum. (Skibo et al. 1996)

The energy dependence of Coulomb and ionisation losses of electrons in the MeV range imply that they cannot travel far from their sources and that their spectrum should be hard. Thus the OSSE result can only be explained by invoking an additional source of low energy electrons with an input power exceeding that provided by Galactic supernovae. Skibo et al. (1996) have argued that this phenomenon may be transient due to Galactic spiral density waves, thereby relaxing the energy requirement. Very promising appear models which explain the soft spectrum of low energy electrons as direct result of stochastic acceleration out of the thermal pool working against Coulomb interactions (Schlickeiser, this volume). The energy input in this class of models would come from interstellar turbulence.

The existence of a high density of low-energy electrons is an important issue for the energy and ionisation balance of the interstellar medium both in the plane and in the halo, since the bulk of the energy input is directly transferred to the thermal gas.

5 The Magellanic Clouds

The Magellanic Clouds are two irregular galaxies located at around 50 kpc distance. The Large Magellanic Cloud (LMC) has been detected by EGRET (see also Fig.8), while for the Small Magellanic Cloud (SMC) EGRET has derived only an upper limit (Sreekumar et al. 1993). Both in LMC and in SMC the γ-ray emissivity per H-atom is considerably smaller than in our Galaxy. This result implies that the bulk of GeV cosmic rays is galactic in origin. Since the gas in LMC and SMC is much less illuminated by cosmic rays than gas in the Galaxy, the cosmic ray density at some distance from the Galaxy may be very small. This has impact on dark matter studies, since this fact allows a substantial amount of baryonic dark matter to be hidden at a few 10 kpc from the Galaxy without inducing observable γ-ray emission.

There has been a debate on whether the γ-ray flux of LMC and SMC in relation to their radio emission would allow equipartition between the magnetic field and cosmic rays. It turns out that this equipartition is still possible provided one allows the cosmic ray electron-to-proton ratio to be different from that in the solar vicinity. The γ-ray data of the Magellanic Clouds are best explained when the e/p ratio is much higher so that basically only the density of cosmic ray nucleons is reduced in LMC and SMC (Pohl 1993).

All results mentioned above were derived based on the integral properties of

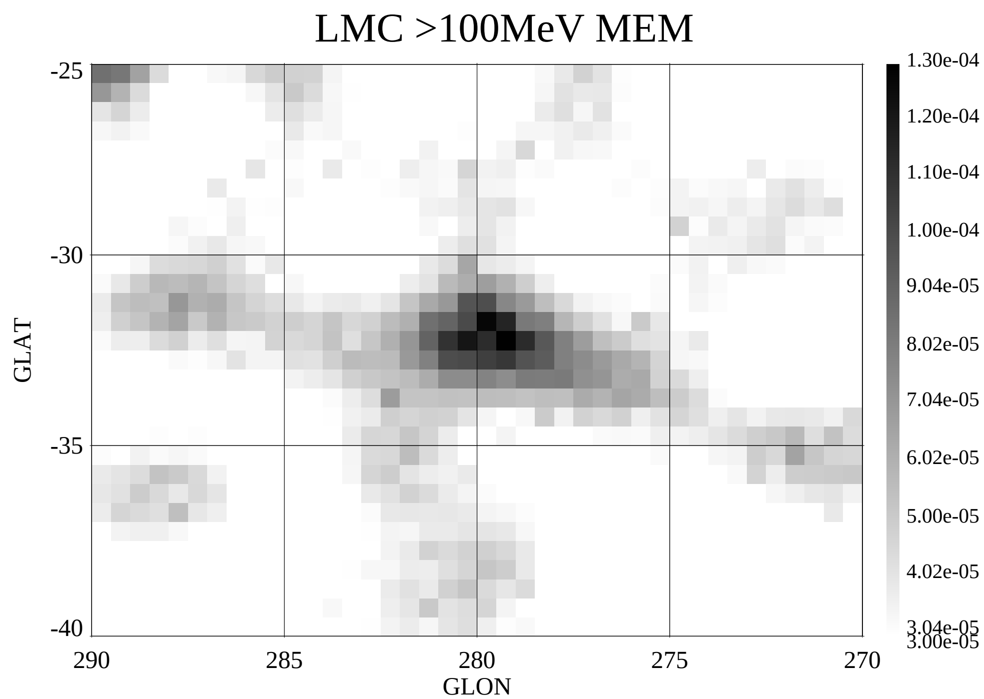

Figure 8: The γ-ray intensity above 100 MeV for the region of LMC. The data are deconvolved again and the scale is in $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}$. LMC is clearly seen with its emission concentrated along the gas ridge south of 30 Doradus.

the Magellanic Clouds. A new study including spatial and spectral information is under way.

6 What of the future?

The next step in analysing γ-ray data of diffuse emission will be based on propagation modelling of cosmic rays which better allows to link the γ-ray data to the results of radio observations and direct cosmic ray measurements. Such models are underway and they may help to answer the question of whether the sources of cosmic rays are localized entities, e.g. supernova remnants, or whether they are diffuse, and in relation to this, whether reacceleration plays a rôle. With forthcoming instruments we also may be able to set more stringent limits on the baryon fraction in a dark matter halo.

The ESA M2 mission INTEGRAL will not be ideally suited for studies of diffuse γ-ray continuum emission from the halo as it is specifically designed for high spatial and energy resolution. However, two project studies currently undertaken are highly promising. The project GLAST will use silicon-strip detectors to measure γ-rays in the energy range 50 MeV to 100 GeV a factor 100 better in sensitivity than EGRET. At low energies of 1 MeV to 50 MeV laboratory studies are undertaken to combine the Compton telescope principle with silicon-strip tracking of the scattered electron, which may also give a factor 100 in sensitivity compared to COMPTEL. So if we continue to invest in γ-ray astronomy we may go a big step forward in understanding diffuse γ-rays from Galactic halos in the next decade.

Acknowledgements: I am indebted to Andy Strong and Jeff Skibo who kindly provided figures and plots in electronic form, partly prior to publication.

References

Chen A., Dwyer J., Kaaret P.: 1996, ApJ, in press
Digel S.W., Grenier I.A., Heithausen A. et al.: 1996, ApJ, in press
Hunter S.D. et al.: 1996, A&AS, in press
Kanbach G., Bertsch D.L., Dingus B.L. et al.: 1996, A&AS, in press
Pohl M.: 1993, A&A 279, L17
Purcell W.R. et al.: 1996, A&AS, in press
Skibo J.G., Ramaty R., Purcell W.R.: 1996, A&AS, in press
Sreekumar P., Bertsch D.L., Dingus B.L. et al.: 1993, PRL 70, 127
Strong A.W.: 1995, Exper. Astron. 6, 97
Strong A.W. et al.: 1994, A&A 292, 82
Strong A.W., Mattox J.R.: 1996, A&A, in press
Thompson D.J., Bertsch D.L., Dingus B.L. et al.: 1995, ApJS 101, 259
Yamasaki N. et al.: 1996, A&AS, in press

Address of the author:

Martin Pohl: Max-Planck-Institut für Extraterrestrische Physik, Postfach 1603, 85740 Garching, Germany; mkp@mpe-garching.mpg.de